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Title

Discussion of Our Earlier Paper 'Hydromagnetic Interpretation of Sudden Commencements of Magnetic Storms'

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On page 3771 of his recent paper in this Journal *Matsushita* [1962] discussed the disagreement of his analysis with ours [*Wilson and Sugiura*, 1961] regarding the polarization rules of the elliptically polarized hydromagnetic waves in the magnetic storm sudden commencements. The purpose of this communication is to correct the misunderstanding that may have resulted from Matsushita's criticism, which appears to be based on an analysis much less extensive and complete than ours. The discussions given below are based on the results of analysis of about six hundred and fifty vector diagrams of the SC horizontal perturbation ΔH.

The material for this analysis was drawn from virtually all the rapid-run magnetograms available at the IGY World Data Center A; the analysis concerns 93 SC's that occurred during the period beginning with the IGY and ending September 1961. Though for a few of these SC's data from only a few magnetic observatories were available, records from seven stations, on the average, were scaled for each SC. In addition, data were collected from 18 to 30 magnetic observatories (out of the 38 observatories listed in Table 2) for ten selected SC's that are evenly distributed over the Greenwich day.

The polarization rules were derived and tested in the following way. First, polarization characteristics were determined for 9 to 67 SC's for 14 observatories (listed in Table 1) and the results were all combined to derive rules by which the polarizations are governed. Secondly, polarization characteristics were examined for 18 to 30 observatories (Table 2) for each of 10 SC's to test whether or not the rules obtained by the first method are obeyed by individual SC's.

These analyses confirmed our previous findings and gave further support to our interpretation of SC's. The general picture of our interpretation of SC's can be summarized as follows.

The primary effect of the impact of a solar gas cloud on the surface of the magnetosphere is to create a longitudinal hydromagnetic shock wave. Since near the equatorial plane the magnetic field is nearly perpendicular to the equatorial plane, the longitudinal hydromagnetic wave propagates toward the earth essentially in this mode. Because of the curvature of the lines of magnetic force, the longitudinal hydromagnetic wave generates transverse hydromagnetic waves by coupling. These transverse hydromagnetic waves are transmitted to the earth essentially along the lines of magnetic force. The coupling is most effective in the outer regions of the magnetosphere where the magnetic field is weak; from these regions the transverse hydromagnetic waves propagate to the earth in high latitudes.

The above picture is greatly idealized; in reality the magnetic perturbation created by the impact of the solar plasma will propagate in a more complex manner. However, we believe that the above mechanism gives the essential structure of the sudden commencement of a magnetic storm. The basis of this belief is the fact that this mechanism explains some of the major features of SC's observed on the earth's surface.

If an SC magnetic perturbation observed at an observatory were a pure transverse hydromagnetic wave, its polarization would be circular, whereas if it were a pure longitudinal hydromagnetic wave, its polarization would be linear. The polarization of a magnetic perturbation can be studied by tracing the end point of the magnetic perturbation vector. Only the projection

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of the magnetic vector onto the horizontal plane is investigated here.

The analysis of the characteristics of 650 such vector diagrams for the first few minutes of SC's has shown that the earth can be divided roughly into three zones according to the polarization of SC's. The polarization characteristics, the ranges in geomagnetic latitude Φ of these zones, and the ranges in geocentric distance R_e (in units of earth radius) of the regions in the magnetosphere which are the projections of the three zones onto the equatorial plane along the lines of magnetic force are:

(*a*) linear polarization for $0° \leq \Phi \leq 40°$ and $1.0 \leq R_e \leq 1.7$.

(*b*) mixture of elliptical and linear polarizations for $40° \leq \Phi \leq 55°$ and $1.7 < R_e \leq 3.0$.

(*c*) elliptical polarization for $55° < \Phi \leq 90°$ and $R_e > 3.0$.

We interpret this result as follows. The SC magnetic perturbation primarily consists of longitudinal hydromagnetic waves in zone (*a*), and of transverse hydromagnetic waves in zone (*c*). Between these two zones there is a transitional zone where either one of these two modes or a mixed mode may be observed.

Table 1 summarizes the results of analysis regarding (1) percentage of SC's that are elliptically polarized, and (2) among these elliptically polarized SC's, percentage of SC's that obey the polarization rules. It is clearly seen that the percentage of elliptically polarized SC's increases with increasing latitude. For the southern hemisphere rapid-run magnetic data are scarce; however, the results for the five observatories used do indicate the same trend.

The sense of rotation, either clockwise or counterclockwise *when viewed downward* on the earth's surface, of the circularly polarized SC's obeys the following two rules:

1. In each of the northern and southern hemispheres the sense of rotation is opposite in two quadrants separated by the meridian plane through 10 hours and 22 hours.
2. In each meridian plane the sense of rotation of magnetic vector is opposite in the northern and southern hemispheres.

TABLE 1. Percentage of SC's That are Elliptically Polarized, and Percentage of SC's (Among these Elliptically Polarized SC's) Obeying the Polarization Rules

1	2	3	4	5		6	
				Elliptically Polarized SC's		SC's Obeying Polarization Rules	
Magnetic Observatory	Geomagnetic Latitude	R_e*, earth radii	Total Number of SC's, N	Number, N_e	$(N_e/N) \times 100\%$	Number, N_e*	$(N_e^*/N_e) \times 100\%$
	°				%		%
Murchison Bay	75.25N	15.5	20	15	75	7	47
College	64.7N	5.4	55	32	58	26	81
Healy	63.6N	5.0	31	22	71	21	96
Sitka	60.0N	4.0	67	52	78	50	96
Lovö	58.2N	3.6	30	14	47	12	86
Fredericksburg	49.6N	2.4	62	23	37	21	91
Tucson	40.4N	1.7	36	11	30	10	91
Honolulu	21.0N	1.14	37	8	21	6	75
Guam	3.9N	1.005	9	0	0	...	...
Apia	16.0S	1.08	9	2	22	1	50
Hermanus	33.3S	1.45	33	16	48	13	81
Watheroo	41.7S	1.78	34	16	47	11	69
Byrd Station	70.6S	9.0	31	20	65	18	90
Wilkes Station	77.8S	22.5	47	36	77	24	66
Total			501	267		220	

* R_e is the geocentric distance of the point at which the magnetic field line (of the unperturbed dipole) through the station crosses the equatorial plane.

TABLE 2. Results of Analysis of Ten SC's

1 Time of SC		2 Stations for Which Data Were Available	3 Stations at Which SC Was Elliptically Polarized	
UT	Date	Number, S	Number, S_e	$(S_e/S) \times 100\%$
0042	July 5, 1957	23	17	74%
0315	Oct. 22, 1958	26	23	88
0843	Sept. 3, 1958	26	18	69
0930	Sept. 16, 1958	29	24	83
1050	Jan. 25, 1958	27	22	81
1300	Sept. 4, 1957	18	16	89
1529	July 31, 1958	30	26	87
1652	May 31, 1958	22	17	77
1821	Nov. 6, 1957	22	21	95
1920	Aug. 29, 1957	24	18	75
		Total 247	Total 202	Mean 82

Stations (Geomagnetic Latitude)

1. Thule (N 89°.0)
2. Godhavn (N 79°.8)
3. Murchison Bay (N 75°.3)
4. Reykjavik (N 70°.2)
5. Point Barrow (N 68°.6)
6. Tromsö (N 67°.2)
7. Kiruna (N 65°.3)
8. College (N 64°.7)
9. Big Delta (N 64°.4)
10. Healy (N 63°.6)
11. Lerwick (N 62°.5)
12. Sitka (N 60°.0)
13. Eskdalemuir (N 58°.4)
14. Lovö (N 58°.2)
15. Valentia (N 56°.7)
16. Rude Skov (N 55°.9)
17. Hartland (N 54°.6)
18. Manhay (N 52°.0)
19. Dourbes (N 52°.0)
20. Fredericksburg (N 49°.6)
21. Ponta Delgada (N 45°.6)
22. Toledo (N 43°.9)
23. Tucson (N 40°.4)
24. Memambetsu (N 34°.1)
25. Kakioka (N 26°.0)
26. Honolulu (N 21°.0)
27. Paramaribo (N 17°.0)
28. Guam (N 3°.9)
29. Koror (S 3°.3)
30. Hollandia (S 12°.5)
31. Apia (S 16°.0)
32. Hermanus (S 33°.3)
33. Watheroo (S 41°.7)
34. Byrd Station (S 70°.6)
35. Little America (S 74°.0)
36. Dumont d'Urville (S 75°.5)
37. Wilkes (S 77°.8)
38. Scott Base (S 79°.0)

In the northern hemisphere the rotation is clockwise from 10 hours to 22 hours; this specifies the sense of rotation in the remaining three quadrants according to the two rules given above.

The two rules can be combined into one: the SC hydromagnetic perturbation is transmitted to the earth in the ordinary mode in the morning hemisphere (22 hours to 10 hours) and in the extraordinary mode in the afternoon hemisphere (10 hours to 22 hours). However, in our earlier paper we represented the mode by the sense of rotation of the magnetic vector; hence, for the sake of uniformity of representation this same way of expressing the mode of hydromagnetic waves is used here.

In the group of elliptically polarized SC's the percentage of cases in which the two rules are obeyed ranges from 91 to 69 per cent, with a mean of 86 per cent (column 6, Table 1), excluding the very high latitude stations (Murchison Bay and Wilkes) and Apia (for which there were too few cases); the percentage of agreement with the polarization rules is independent of latitude. It is noteworthy that even for stations at which circularly polarized SC's are not very frequent, e.g., Fredericksburg, Tucson, and Honolulu, the majority of circularly polarized SC's follow the pattern set by the rules.

In the foregoing discussions the rules were derived statistically treating the time variable, 'local time,' at each station as being equivalent

TABLE 2. (Continued)

1 Time of SC		4 Stations at Which Elliptically Polarized SC Obeyed the Rules		5 Same as Columns 3 and 4, Excluding Stations With $\Phi > 72°(R_e > 10.5)$		
UT	Date	Number, S_e*	$(S_e{}^*/S_e) \times 100\%$	$S_e'(S_e$ with $\Phi < 72°)$	$S_e'^*$	$(S_e'^*/S_e') \times 100\%$
0042	July 5, 1957	12	70%	12	10	83%
0315	Oct. 22, 1958	19	83	18	17	95
0843	Sept. 3, 1958	13	72	14	11	79
0930	Sept. 16, 1958	23	96	18	17	95
1050	Jan. 25, 1958	16	73	16	11	69
1300	Sept. 4, 1957	13	81	11	10	91
1529	July 31, 1958	17	56	20	15	75
1652	May 31, 1958	14	82	13	13	100
1821	Nov. 6, 1957	13	62	17	11	65
1920	Aug. 29, 1957	17	95	13	12	92
		Total 157	Mean 77	Total 152	Total 127	Mean 84

to the spatial variable, 'longitude with respect to the sun,' at a fixed moment of time. It is desirable, therefore, to test to what extent individual SC's follow the rules. For this purpose analysis was made on ten SC's (listed in Table 2). The stations used are listed in Table 2; the number of stations for which it was possible to analyze the data with an acceptable accuracy is shown in column 2.

For the ten SC's, the percentage of stations at which SC's were elliptically polarized ranges from 69 to 95 per cent (column 3), indicating a high rate of occurrence of elliptically polarized SC's. Taking the cases in which SC is observed to be elliptically polarized, the number and the percentage of stations at which the polarization of SC was in agreement with that expected from the polarization rules are given in column 4. The agreement between the observed and the predicted pattern of SC polarization can be considered good. The average of the above percentage $(S_e{}^*/S_e) \times 100$ per cent (column 4, Table 2) is 77 per cent; the corresponding percentage in the statistical analysis discussed earlier is 84 per cent (column 6, Table 1).

Recent plasma measurements by Mariner 2 indicate that *steady* solar wind exists in interplanetary space [*Neugebauer and Snyder*, 1962], and because of this continuous flow of solar plasma the magnetosphere is confined in a 'cavity.' Observational evidence for the 'cavity surface' has been provided by magnetic measurements made with instruments aboard Pioneer 1 [*Sonnett et al.*, 1960], Pioneer 5 [*Coleman et al.*, 1960], Explorer 10 [*Heppner et al.*, 1962], and Explorer 12 [*Cahill and Amazeen*, 1963]. The measurement by Explorer 10 indicated that the cavity surface extends to distances greater than 20 earth radii on the dark side of the earth. On the day side of the earth the cavity surface is near 10 earth radii.

For an unperturbed centered dipole the magnetic field lines crossing the equator at a geocentric distance of 10 earth radii intersect the earth's surface at 72° latitude. Because of the magnetic field produced by the electric current on the boundary surface, the field lines will be distorted. Theoretical studies of the shape of the cavity surface have been made by a number of workers [*Dungey*, 1961, 1962; *Hurley*, 1961; *Midgley and Davis*, 1962; *Slutz*, 1962; *Spreiter and Briggs*, 1962; *Mead*, 1962]. However, the idealizations and approximations used in these studies make it difficult to determine the distortions of the magnetic field lines that are anchored in the earth near the magnetic poles. Magnetic measurement in the magnetosphere over the polar regions has not been made.

Thus it is not certain whether the magnetic field lines intersecting the earth's surface near the magnetic poles are all crossing the equator on the dark side of the earth, as has been suggested by *Johnson* [1960], or some of these lines of force are connected to those of interplanetary magnetic fields or to the disordered lines of force of the irregular magnetic field that has been observed by Pioneer 1, Pioneer 5, Explorer 10, Explorer 12, and Explorer 14 and has been discussed by *Dessler* [1962]. If the magnetic field lines originating near the magnetic poles are not interhemispherically connected, the modes, i.e. ordinary or extraordinary, of the transverse SC waves may not agree between high-latitude stations in the adjacent northern and southern quadrants. Even if these lines of force are connected on the dark side of the earth at distances greater than 10 earth radii, the magnetic field may be too weak for an efficient coupling of longitudinal and transverse hydromagnetic waves. The dipole field at 10 earth radii is about 30 γ, and the SC amplitudes are about 100 γ or even greater in high latitudes. Even if the focusing of the wave energy in the propagation toward the earth is taken into account, the amplitude of the SC perturbation is of the same order of magnitude as, or greater than, the unperturbed field. Then the coupling and transmission of hydromagnetic waves may be much more complicated than those expected from the linearized theory.

In any event there is reason to suppose that the SC polarization rules may not be satisfied in the regions near the magnetic poles. How large is the extent of these regions is as yet a matter

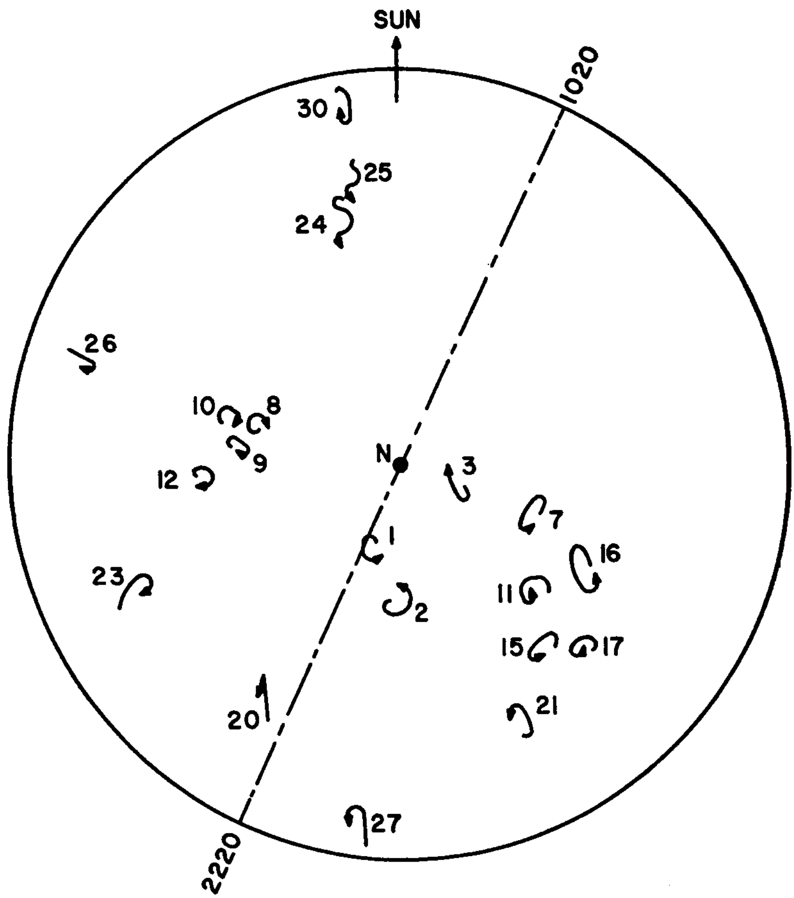

Fig. 1. Map of the horizontal perturbation vector (ΔH) diagrams for the sudden commencement of 0315 UT October 22, 1958, for twenty magnetic observatories in the northern hemisphere. The vector diagrams are drawn at the projected positions of the stations on the equatorial plane. The numbers by each vector diagram refer to the station identification list in Table 2. The meridian plane separating the two zones of opposite polarization (extraordinary mode 1020 to 2220 hours and ordinary mode from 2220 to 1020 hours) is shown.

of speculation. However, it is of interest to set some upper boundaries in latitude, one in each hemisphere, above which the mode of transverse SC waves is at random.

If we set these boundaries at geomagnetic latitudes $\pm 72°$ (as was indicated earlier, the lines of force crossing the earth's surface at 72° latitude intersect the equatorial plane at a geocentric distance of 10 earth radii) then, for the stations with latitude greater than 72°, on the average only 53 per cent of the SC's obey the polarization rules, indicating that such boundaries as defined above appear to exist near 72°. In column 5 of Table 2 the percentage of stations with latitude less than 72° for which elliptically polarized SC's obey the polarization rules is given; the average percentage is now increased to 84 from 77 per cent, which is the corresponding percentage when all the stations are included (column 4). Though the difference is very slight, the percentage does increase by excluding the stations in the polar cap.

The vector diagrams for the first few minutes of the SC of November 22, 1958, at 0315 UT, for 20 stations in the northern hemisphere are shown in Figure 1. The position of each station is projected onto the equatorial plane along the line perpendicular to this plane, and the vector diagram for the station is placed at the projected position of the station. The vector diagram is drawn as if the plane of the projection were the horizontal plane at the station, and the vector diagram is so oriented that the direction of the magnetic north for the vector diagram is pointed toward the center. The scales are not uniform for all the stations. The number by each vector diagram identifies the station according to the list of stations in Table 2.

The SC is elliptically polarized and satisfies the polarization rules at 14 of the 20 stations. The meridian by which two modes are separated is approximately through 10h 20m and 22h 20m [*Wilson*, 1962].

At station 3, Murchison Bay, the sense of rotation is opposite to that expected from the rules; however, the line of magnetic force (of the unperturbed dipole) through this station crosses the equator at 15.5 earth radii.

At station 26, Honolulu, and at station 27, Paramaribo, the vector diagram exhibits a hooked form that can be interpreted as an indication of the initial arrival of a predominantly

TABLE 3. Analysis of SC Vector Diagrams of Looped or Hooked Form

1 Station	2 Geomagnetic Latitude	3 Time of SC Date	UT	LT	4 Rotation Expected From Rules	5 Rotation in Loop or Hook, Observed	6 Form of Vector Diagram
	°						
Honolulu	21.0	Feb. 11, 1958	0125	1425	*C*	*CC*	*l*
		Aug. 6, 1957	0508	1808	*C*	*C*	*h*
		Oct. 28, 1958	0650	1950	*C*	*C*	*h*
		July 8, 1958	0748	2048	*C*	*C*	*h*
		July 2, 1957	0857	2157	*C*	*C*	*h*
		Sept. 22, 1957	1345	0245	*CC*	*CC*	*h*
Tucson	40.4	July 5, 1957	0042	1742	*C*	*C*	*h*
		June 7, 1958	0046	1746	*C*	*C*	*h*
		Sept. 16, 1958	0930	0230	*CC*	*CC*	*h*
		Dec. 19, 1957	0937	0237	*CC*	*CC*	*h*
		Aug. 29, 1957	1920	1220	*C*	*C*	*h*
Fredericksburg	49.6	Sept. 29, 1957	0016	1916	*C*	*C*	*h*
		July 7, 1957	0042	1942	*C*	*C*	*h*
		Jan. 5, 1959	0137	2037	*C*	*C*	*h*
		May 24, 1959	0540	0040	*CC*	*C*	*h*
		Dec. 19, 1957	0937	0437	*CC*	*CC*	*h*
		Jan. 29, 1960	1937	1437	*C*	*C*	*l*
Lerwick	62.5	July 31, 1958	1529	1529	*C*	*C*	*l*
Lovö	58.2	July 31, 1958	1529	1629	*C*	*C*	*l*
Rude Skov	55.9	July 31, 1958	1529	1629	*C*	*C*	*l*
Hartland	54.6	July 31, 1958	1529	1529	*C*	*C*	*l*

longitudinal wave followed by the arrival of a transverse wave. The sense of rotation of the magnetic vector in the hooks for stations 26 and 27 agrees with that expected from the polarization rules for higher latitudes.

These hooked forms frequently occur at middle to low latitues on the side of the earth away from the sun. There is often a counterpart on the day side of the earth where the vector diagram has an initial loop followed by a linear increase in H. However, such a feature is not apparent in the example shown in Figure 1.

To demonstrate that the polarization rules are obeyed by those SC's that exhibit a hook or an inverted hook in their vector diagrams, the sense of rotation of the magnetic vector for the hooked part is shown in Table 3. Column 4 of Table 3 indicates for each observatory SC the sense of rotation, clockwise (C) or counterclockwise (CC), expected from the quadrant polarization rules. The sense of rotation actually observed in the hooked part of each SC is shown in column 5. Agreement between columns 4 and 5 is good; 80 per cent of the 17 observatory SC's listed in Table 3 for Honolulu, Tucson, and Fredericksburg show agreement.

For the SC of July 21, 1958, at 1529 UT the four stations, Lerwick, Lovö, Rude Skov, and Hartland, were all on the day side of the earth. The vector diagrams for these stations showed a loop or inverted hook form, and the polarization characteristics were in agreement with those expected from the rules.

In column 6 of Table 3 the form of the vector diagram in each SC is indicated; here l and h signify loop and hook forms, respectively.

With the data presented in this communication we believe that the polarization rules for the magnetic storm commencements are well founded.

More detailed discussions of our analysis will be presented later.

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